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## Circumbinary disks around T Tauri stars: HST/NICMOS near-infrared images and polarimetric maps

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**Abstract.** We have obtained new near-infrared images of both GG Tau and UY Aur circumbinary disks with the polarimetric modes of NICMOS aboard the Hubble Space Telescope. The  $1\mu\text{m}$  intensity map of GG Tau reveals a more complete elliptical shape than in previous ground-based images. Its eastern and western sides are definitely asymmetric. Our image strongly supports the ring geometry proposed by Guilloteau, Dutrey & Simon (1999) on the basis of their millimetre interferometry images: a geometrically thick and sharply edged ring surrounding an empty gap around the binary. Around UY Aur, we identify structures that are in excellent agreement with the optical images of Ménard et al. (1999), which confirms that the inclination of the system to the line-of-sight is about 60 degrees. We also find tentative new structures closer to the stars.

### 1. Introduction

The presence of circumstellar disks around T Tauri stars has been suspected for a long time, but it is only very recently that these disks were directly detected, using high-angular millimetre imaging. These images revealed extended gas structures which appeared to be in Keplerian rotation around the central object. Among the rare detections so far, two disks were found around binary T Tauri stars: GG Tau (Dutrey, Guilloteau & Simon 1994) and UY Aur (Duvert et al. 1998). The separations of the binaries are  $0''.25$  and  $0''.89$  respectively, which correspond to projected physical separations of 35 and 125 AU at the distance of the Taurus star-forming region (140 pc).

In both cases, light scattered off the surface of the disks has been detected afterwards with adaptive optics imaging at near-infrared wavelengths. Roddier et al. (1996) found that the GG Tau ring has a clumpy appearance and that several radial spokes of material extend from the ring onto the central stars. The ring is brighter in its northern part, but is detected in all directions. They interpret this brightness difference as being due to the scattering geometry. The UY Aur case is very different, as Close et al. (1998) only detected the disk on one side of the binary. Furthermore, they found evidences that a “spiral arm” splits from the main disk and gets closer to the star. Deconvolution processes were applied in both studies to retrieve the highest spatial resolution allowed by adaptive optics devices, and this may lead to some artifacts in the final images.

More recently, the first visible wavelength images of UY Aur were obtained by Ménard et al. (1999) at 600 and 800 nm with HST/WFPC2. The PSF-subtracted images revealed a more complicated structure that was found by Close et al. (1998): a large “clump” appears to be independent from the disk itself. If true, this implies that the inclination of the system to the line-of-sight is larger than was first thought (about  $60^\circ$  instead of about  $40^\circ$ ).

To improve our knowledge of these two circumbinary disks, we have performed new observations at  $1\mu\text{m}$  and  $2\mu\text{m}$  of these systems with HST/NICMOS. We used the polarimetric modes, and we obtained both intensity and polarization maps, which do not need to be deconvolved. The GG Tau polarization maps are the first ever obtained of this system, while Potter et al. (1998) already presented a deconvolved J-band polarization map of UY Aur which revealed a nice centrosymmetric pattern. Polarization maps are powerful tools to investigate the dust grain properties and the geometry and structure of the disks.

In section 2, we summarize our observations and data processing steps, and the maps of both systems are presented and commented in section 3. Section 4 describes some implications of our results on the properties of these disks.

## 2. Observations and data processing

The  $1\mu\text{m}$  and  $2\mu\text{m}$  images were obtained with Camera 1 and Camera 2 respectively, providing pixel scales of  $0''.043$  and  $0''.075$ . Both binaries were observed through the three polarizers at each wavelength, during three 96 seconds exposures for each filter. The regular NICMOS data reduction pipeline proved to be unsatisfying, and we had to re-reduce all data, with specific care to the so-called “pedestal effect”, to obtain final images where the sky level is flat all over the detector.

To allow clear detections of the disks, it is mandatory to remove the bright stellar point spread functions (PSFs). We first tried Tinytim PSFs, but it appeared that their match with the real ones is quite poor, so we turned to a “natural” star, i.e. a bright single star observed through the same filters. The diffraction spikes subtraction, though imperfect, is quite good, and the optical ghosts induced by some polarizers are naturally removed. Some residuals in the core of the PSFs, however, are still large, and nothing can be securely detected in the inner  $0''.5$  at  $1\mu\text{m}$ . At  $2\mu\text{m}$ , some fringing can be seen at separations as large as  $3''.5$ . No deconvolution process was applied to our images, which allows an easier interpretation.

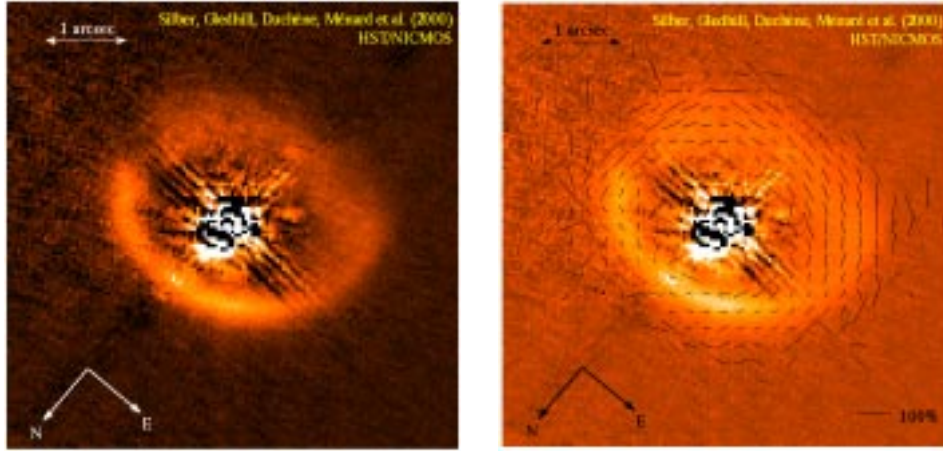


Figure 1. PSF-subtracted intensity (left) and polarization (right) maps of GG Tau at  $1\mu\text{m}$ .

### 3. Results

#### 3.1. GG Tau

The new  $1\mu\text{m}$  image of the GG Tau ring is presented in Fig. 1. Its overall geometry is in good agreement with Roddier et al. (1996)’s images, though with a higher signal-to-noise ratio. However, there are some noticeable features. First, the ring does not appear clumpy in our image. This property was likely an artifact introduced by the deconvolution process applied to the adaptive optics images. Fitting an ellipse onto the ring, we find a semi-major axis, a position angle and an inclination in excellent agreement with the millimetre results of Guilloteau et al. (1999). It is noticeable, however, that this ellipse is not centered on the center of mass of the binary. Our image does not allow us to confirm the existence of the spokes of material discovered by Roddier et al. (1996), because of the large PSF subtraction residuals inside the ring. Finally, a significant east-west asymmetry in the northern part of the ring is seen in our intensity map.

The polarization vectors are strikingly well organized in a centrosymmetric pattern, which is symmetric about the semi-minor axis of the ring. The brightest part of the ring, which is the closest to the observer, displays a lower polarization level than the faintest side, typically 20% as opposed to 50–60%.

At  $2\mu\text{m}$ , the disk is too close to the stars, and the large subtraction residuals prevent us from obtaining a clear image of the ring. However, we calculated the polarization map at this wavelength and, though the image is strongly dominated by the unpolarized stellar fluxes, a centrosymmetric pattern is found in the polarization vectors, with a typical level of 5–10%, indicating that the intrinsic polarization level of the light scattered by the ring is high.

#### 3.2. UY Aur

The morphology of the UY Aur circumbinary disk in our new  $1\mu\text{m}$  image is in good agreement with Ménard et al. (1999)’s optical image, though the former

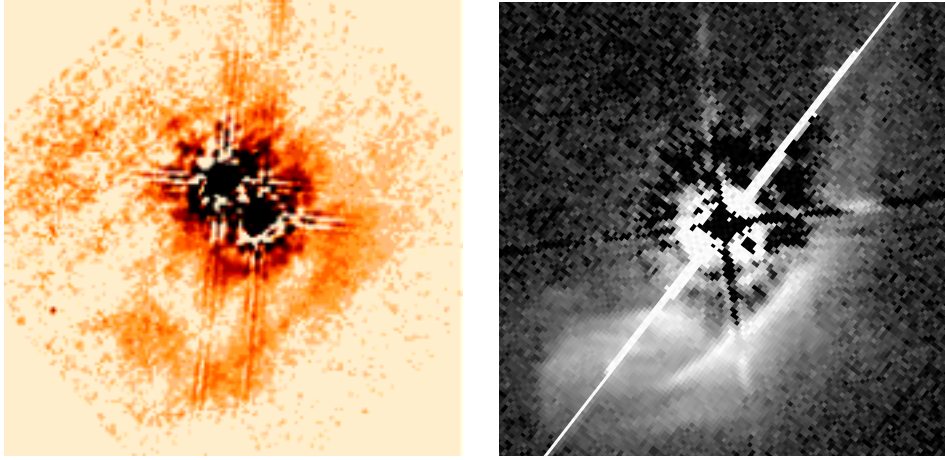


Figure 2. Intensity maps of UY Aur at  $1\mu\text{m}$  (this work) and at  $600\text{ nm}$  (from Ménard et al. 1999). Image sizes are  $7''.7$  and  $12''$  respectively. North is up, East to the left. The noisy area located to the East of the binary in the  $1\mu\text{m}$  image is due to a very low response of the detector.

suffer from a poor signal-to-noise ratio. As can be seen in Fig. 2, the disk appears as an unresolved arc to the Southwest of the binary at both wavelengths, while a bright clump to the southeast appears to be unrelated to this structure. Noticeably, the bright arc seems to widen to the West of the binary in our image. This can be interpreted as the arc breaking into two separate arcs: the disk itself remaining at least  $2''.5$  away from the stars, and an inner arc, getting closer to the stars. The latter would correspond to the “spiral arm” described by Close et al. (1998). A second feature in our map is an inner arc which is much brighter than the disk itself. It lies about  $1''$  to the Southwest of the secondary. This may be a PSF artifact, but it can be seen using both a natural or a Tinytim-built PSF. Furthermore, its coincidence with a similar arc detected in the WFPC2 images is suggestive (see Fig. 2). At  $2\mu\text{m}$ , the only area which is clearly separated from the PSF residuals is found to the southeast of the binary. It can be traced up to  $5''$  away from the stars. The back side of the disk remains undetected at both wavelengths, which provides strong constraints on the dust grain properties. We note however, that the small arc seen to the Northeast of the primary at  $1\mu\text{m}$  can be seen in all individual images.

The polarization pattern at  $2\mu\text{m}$  is well organized in its southeastern part, with all vectors well aligned, in a fashion consistent with centrosymetric. The typical polarization level is about 40%. At  $1\mu\text{m}$ , however, the picture is much different: though the vectors are basically aligned in the southwestern part of the disk with a typical level of 20%, again in a more or less centrosymmetrical pattern, they are quite randomly oriented in the southeastern clump. Whether this is due to our reduction pipeline, to the low signal-to-noise ratio or reflects the intrinsic pattern is unclear. It must be noted that Potter et al. (1998) found a very different behaviour. Their data reduction process, however, included a deconvolution step, which impact on the polarization is unknown.

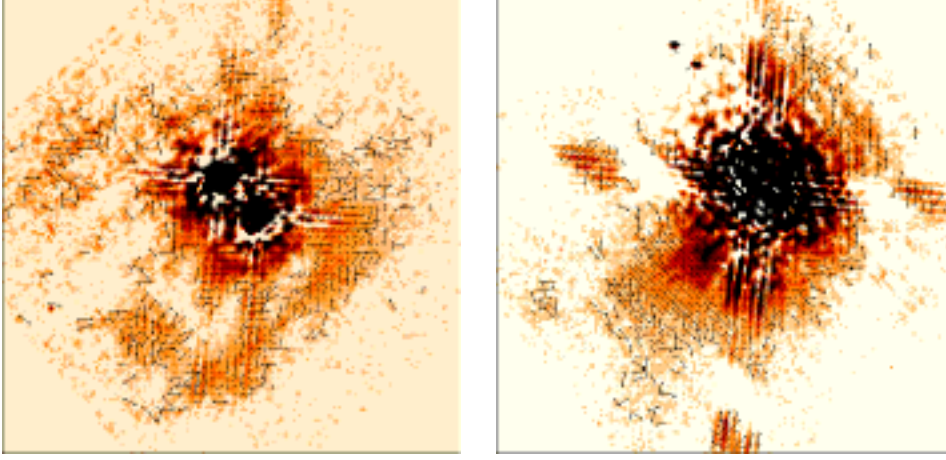


Figure 3. Polarization vectors superimposed on the intensity maps of UY Aur at  $1\mu\text{m}$  (left) and  $2\mu\text{m}$  (right). Image sizes are  $7''.7$  and  $13''$  respectively. Orientation of both images is the same as in Fig. 2.

#### 4. Implications and open questions

##### 4.1. GG Tau

As already pointed out by Guilloteau et al. (1999), the shift between the apparent center of the ring and the center of mass of the binary is naturally explained by a thick ring geometry. This is related to the fact that, in the Mie theory, forwards scattering is strongly favoured. Hence, most of the light scattered towards the observer comes from the upper part of the disk's inner edge, whose projection onto the sky is not symmetric about the physical center of the ring. The quantitative model proposed by Guilloteau et al. (1999) is a ring with a half-thickness of 60 AU at its inner radius (180 AU) and a very sharp edge. The observed location of the ring appears to be in excellent agreement with the prediction from this model. Roddier et al. (1996) suggested that the thickness-to-radius ratio was about one tenth at the inner edge of the ring, which seems incompatible with our results.

The origin of the east-west asymmetry is unclear. It may be due to the presence of two illuminating stars, or be related to the slight asymmetry found in the millimetre wavelength image, which itself may reveal internal structures differences.

##### 4.2. UY Aur

Fitting ellipses on the large southwest unresolved arc both at  $1\mu\text{m}$  and 600 nm yields very similar figures and, especially, an inclination to the line-of-sight of about  $60^\circ$  in both cases. This is much larger than the  $42^\circ$  estimated by Close et al. (1998). The reason for that discrepancy is that they assumed that the southeast clump belongs to the disk, which now seems unlikely. Duvert et al. (1998) pointed out that a larger inclination ( $60\text{--}70^\circ$ ) is in better agreement with the millimetre observations.

If the inner arc close to the secondary star proves to be real, it will represent a challenge for theoretical studies, as most of them predict that structures at such a location should be highly unstable due to the interaction with the binary system.

### **4.3. Monte Carlo modelling**

The polarization levels, as well as the front-to-back side flux ratios, are tightly linked to the disk geometry and to the dust grain properties. Our next step in this study is to run Monte Carlo simulations to investigate these properties. For instance, we may determine whether the dust grain size distribution in the disks is compatible with that of interstellar grains. In principle, we will also constrain the amount of “flaring” in both disks, as well as their geometrical height and optical depth.

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